Advances in Mechanical and Materials Engineering

Volume 41, 2024, Pages 125-136
https://doi.org/10.7862/rm.2024.12

THE FACULTY OF MECHANICAL ENGINEERING AND AERONAUTICS
RZESZOW UNIVERSITY OF TECHNOLOGY

Review

Current Possibilities for Recycling Industrial Metallic Wastes: Potential of KOBO Extrusion Process

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Received: 5 August 2024 / Accepted: 28 August 2024 / Published online: 30 August 2024

Abstract

The paper addresses the issue of utilizing industrial wastes considering the current legal regulations in Poland and the European Union. The importance of recycling was highlighted, with particular emphasis on metal elements whose natural deposits are limited. A comparison was made between primary methods of metal extraction and metal recovery (from secondary sources) using solid-state recycling methods without melting. An analysis of some methods for recycling industrial metallic wastes was conducted. Special attention was given to metal chips and the accompanying lubricating and cooling substances. An innovative recycling process was presented – the KOBO extrusion of metallic wastes in the form of chips, with example research results and a list of benefits from using this process for the production of metal profiles.

Keywords: recycling, post-production wastes, utilizing industrial wastes, legal regulations, KOBO extrusion

1. Introduction

The current state of legal regulations concerning waste utilization, in reference to numerous publications on metal recycling (Waste Management in the European Union, Circular Economy, Recycling), demonstrates the possibilities for their use and provides a basis for assessing the selection of recycling methods and their effects. This is crucial from the perspective of the types of metallic materials and the nature and properties of industrial wastes.

The growing global population results in increased metal consumption, leading to the generation of larger quantities of waste (Zante et al., 2024). According to the European Parliament directive, waste is defined as any substance or object which the holder disposes of or is required to dispose of pursuant to the provisions of national law in force (European Parliament and the Council of the European Union, 2008). All EU members must adhere to the waste hierarchy presented in Fig. 1 (European Parliament and the Council of the European Union, 2008; Grabas, 2015).

First and foremost, waste generation should be prevented. If this is not possible, waste should be prepared for reuse, recycled, recovered in some other way, or disposed of (European Parliament and the Council of the European Union, 2008). Waste processing aims to meet the demand for secondary raw materials while increasing the security of raw material supply and stimulating innovative solutions (Nowicka, 2020). The European Commission mandates the increased use of recycled secondary raw materials in new products (European Commission, 2020a). The sustainable use of materials and the reduction of negative environmental impact are ensured by applying a circular economy (McKinsey & Company, 2016; Ellen MacArthur Foundation, 2013). The circular economy model is presented in Fig. 2.

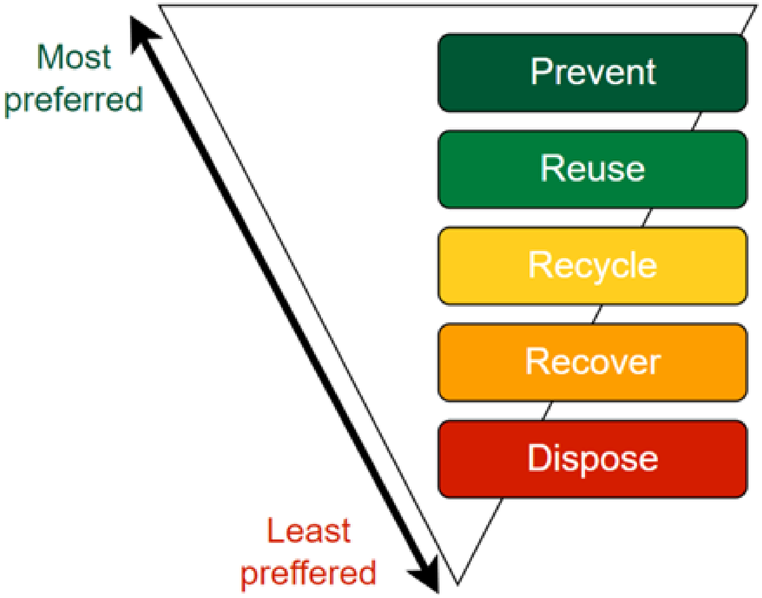


Fig. 1. Waste hierarchy in the EU (Grabas, 2015).

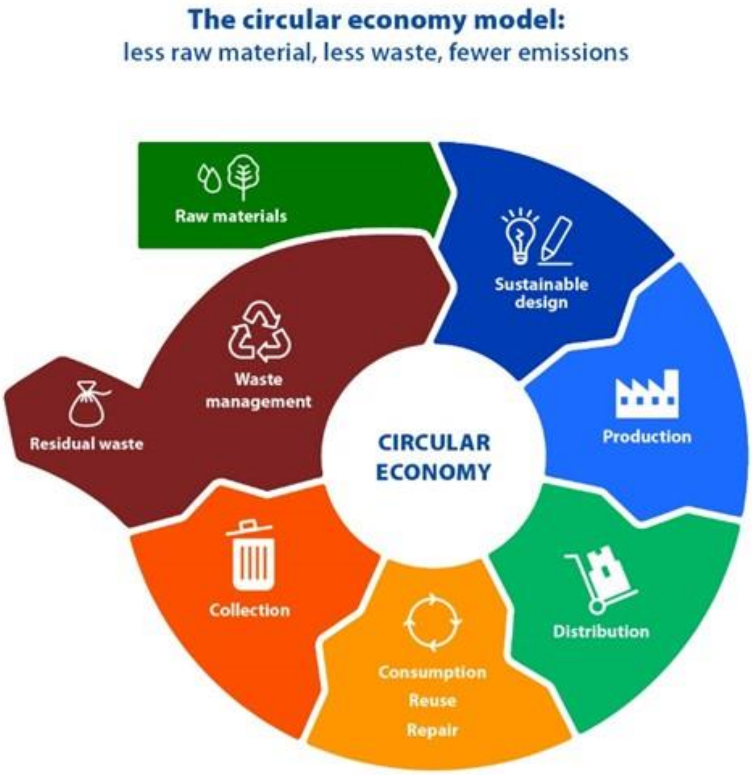


Fig. 2. Circular economy model (European Parliament, 2023).

The transition from the current linear economy to a circular economy brings long-term benefits (Kwiecień, 2018; Nowicka, 2020). This shift aims to achieve a 55% reduction in greenhouse gas emissions by 2030 and zero pollution by 2050 (Fetting, 2020), while it is forecasted that by then, the consumption of natural resources will double (Pietrzyk-Sokulska, 2016; European Commission, 2021). To reach these goals, Europe needs a competitive, green, and more digitalized industry (European Commission, 2020b). It is anticipated that the value of the global green market will be around 2 trillion dollars by 2028. By 2030, the circular economy could be worth as much as 4.5 trillion dollars (Degórski, 2018).

An essential part of the circular economy is the development of new, eco-friendly, and innovative solutions as well as technological transformation (Degórski, 2018; Nowicka, 2020; Zante et al., 2024). The industrial sector is responsible for 50% of total pollution emissions (European Commission, 2024). In the EU, industrial processes and product use accounted for approximately 9.10% of greenhouse gas emissions in 2019 (European Parliament, 2018). It is also estimated that 23% of global greenhouse gas emissions arise from the extraction and processing of natural resources. The application of eco-design ensures easier recycling at later stages (Nowicka, 2020). In highly developed countries, recycling rates can reach up to 50% (Pietrzyk-Sokulska, 2016).

Recycling is the process of recovering waste, whereby waste becomes a useful product again (European Parliament and the Council of the European Union, 2008). It is estimated that until a few years ago, 92% of raw materials used only once were disposed of (Degórski, 2018). Increased consumption leads to the exploitation of natural resources (Kwiecień, 2018). As a result, non-renewable raw materials are depleting and could eventually disappear completely (Degórski, 2018; Pietrzyk-Sokulska, 2016). Therefore, secondary raw materials from the recovery process, which can be reused in production, are gaining importance (Pietrzyk-Sokulska, 2016). Although metal recovery is challenging due to the varied composition of materials withdrawn from use (European Parliament and the Council of the European Union, 2008), recycling leads to reduced operational costs (Kwiecień, 2018) and is a less energy-intensive process compared to sourcing raw materials from primary sources (Pietrzyk-Sokulska, 2016). Recovery also ensures resource security and competitiveness in the EU by reducing dependency on raw material imports from other countries (Degórski, 2018; Pietrzyk-Sokulska, 2016).

Manufacturing metal products generates a large amount of waste (chips, scraps, defective products, or those not meeting standards). The most common method of recycling this waste is melting it down. However, this process has a significant limitation. Scrap in the form of chips undergoes oxidation during the melting process, resulting in the loss of a substantial portion of the material, even up to 60% (Dybiec, 2010), which makes this method inefficient despite the preliminary briquetting before melting (Tucholski, 2013).

There is also the aspect of environmental pollution due to the presence of lubricants, coolants, and other substances used in the production of metal products (Dybiec & Kabalak, 2009).

A key aspect in choosing a recycling method is considering all factors that influence the positive outcome of the process. These include preparation and implementation costs, environmental impact (expected to have no negative impact), and the benefits of using the chosen method and the potential for using post-recycled products.

2. Methods of recycling industrial metallic wastes

Metals, which constitute 4% of all waste globally (Maloney et al., 2020), can be recycled multiple times without losing their properties and quality (Born & Ciftci, 2024; Dubreuil et al., 2010). Recycling ferrous metals consumes 74% less energy, 40% less water, and generates 58% less carbon dioxide emissions compared to extraction from ores. In contrast, recycled aluminum uses 90-95% less energy, while copper recycling requires 85% less energy than production from ores (Krall et al., 2024; Maloney et al., 2020).

Table 1 presents the end-of-life recycling input rates for the EU. The recycling rates for the listed materials vary significantly. The very low rates for some of them are attributed to (European Commission, Joint Research Centre, 2018):

- the unprofitability of recycling,
- the lack of appropriate recycling technology,
- use in long-lasting products,
- increasing demand for these materials.

Alloys of aluminum and iron, which are widely used in industrial production processes, are easy to recover and separate using mechanical sorting and pyrometallurgical processes. However, pyrometallurgical recovery methods consume a significant amount of energy. Hydrometallurgical methods generate considerable waste and require large quantities of water and other chemicals. Both hydrometallurgical and pyrometallurgical methods also produce hazardous gases and wastewater, whose treatment can be costly (Li et al., 2022; Zante et al., 2024).

Aluminum and its alloys can be recycled using conventional remelting methods as well as innovative solid-state recycling methods or without remelting (Gronostajski et al., 2000; Rietdorf et al., 2024). During remelting, liquid aluminum should be treated as a hazardous material due to its high susceptibility to fires and explosions (Dion-Martin et al., 2021; Park et al., 2022).

Table 1. End-of-life recycling input rates for the EU (European Commission. Joint Research Centre, 2018).

Element	End-of-life recycling input rates	Element	End-of-life recycling input rates
Li	0%	Pd	9%
Be	0%	Pr	10%
K	0%	Ru	11%
Sc	0%	Pt	11%
Ga	0%	Mn	12%
Si	0%	AI	12%
Nb	0%	Mg	13%
In	0%	Ir	14%
Dy	0%	Cu	17%
Be	0.6%	P	17%
F	1%	Ti	19%
He	1%	Au	20%
Te	1%	Cr	21%
Ba	1%	Tb	22%
HF	1%	Sb	28%
Ta	1%	Mo	30%
Bi	1%	Fe	31%
La	1%	Zn	31%
Ce	1%	Y	31%
Nd	1%	Sn	32%
Sm	1%	Ni	34%
Gd	1%	Co	35%
Ho	1%	Eu	38%
Tm	1%	W	42%
Yb	1%	V	44%
Lu	1%	Re	50%
S	5%	Ag	55%
Rh	9%	Pb	75%

During the manufacturing process of metal products, significant amounts of waste are generated in the form of chips (Pawłowska & Śliwa, 2017). Aluminum chips can be divided into those resulting from machining or abrasive processes (Lee et al., 2017). Aluminum chips constitute 13.7% and steel chips 14.6% of the waste in the manufacturing industry worldwide (Dhiman et al., 2021). One study showed that cooling and lubricating substances account for about 20% of industrial chips (Rietdorf et al., 2024). Depending on the machining process used, the volume of chips compared to the volume of the machined material is 15 to 30 times greater. The geometry of the chips depends on the cutting speed, cutting depth, the tool used, and the properties of the material from which the workpiece is made (Lee et al., 2017). The burning of residual oils, emulsions, and coolants on the surface of the chips during remelting releases very dangerous gases (Rietdorf et al., 2024; Topolski et al., 2021).

Cooling and lubricating fluids used in machining can be divided into straight oils, soluble oils (emulsions), synthetic fluids, and semi-synthetic fluids. Metal chips can be separated from the lubricating and cooling agents. Table 2 presents some methods for separating lubricating and cooling fluids from chips. Magnetic separation is characterized by low maintenance costs and small size of the separator but it can only be used for materials exhibiting magnetic affinity. Centrifugal separation works well with oils but has a low fluid flow rate, making it difficult to remove large amounts of fluid. Membrane application removes bacteria and it is easy to use, but it has a slow filtration time and high membrane costs. The chemical method effectively removes organic substances but requires a large amount of space, is costly, and generates a large amount of waste. The biological method generates a small amount of waste and effectively dissolves organic substances, but it requires specialized equipment. (Lee et al., 2017).

Table 2. Advantages and disadvantages of recycling methods for cooling and lubricating fluids mixed with metal chips (Lee et al., 2017).

Method	Advantages	Disadvantages
Magnetic separation	Low maintenance costs and small size of the separator	Can only be used for materials with magnetic affinity.
Centrifugal separation	Effective removal of oils from chips	Low fluid flow rate makes it difficult to remove large quantities of fluids
Membrane application	Removes bacteria and is easy to use	Slow filtration time and high membrane costs
Chemical	Effectively removes organic substances	Requires a large amount of space, is costly, and generates a large amount of waste
Biological	Generates a small amount of waste and effectively dissolves organic substances	Requires specialized equipment

Materials such as titanium (Ti) and its alloys, nickel (Ni) and its alloys, and other superalloys present challenges in recycling because they require high processing forces and are difficult to machine. These high forces often lead to damage of die components or tools. Therefore, it is necessary to develop new technologies or innovatively use existing technologies to ensure sustainable and efficient recycling of metal chips (Dhiman et al., 2021).

Machining materials such as titanium generates a very large amount of waste in the form of chips. It is estimated that the mass of chips compared to the total mass of the machined object constitutes 55% (Dhiman et al., 2021). In specific cases, such as the production of biomedical or aerospace parts from titanium, the waste in the form of chips can even constitute up to 80% (Topolski et al., 2017).

Recycling aluminum and its alloys from the secondary market allows for the savings of up to 20 times more energy compared to obtaining it through extraction (Krall et al., 2024; Shamsudin et al., 2016). The use of metal remelting processes is inefficient due to oxidation and the formation of waste in the form of slags (Rietdorf et al., 2024). Recycling chips using conventional remelting is characterized by a recovery rate of about 60% (Rietdorf et al., 2024; Shamsudin et al., 2016).

On the other hand, direct conversion methods (DCM) transform metal chips (MC) into briquettes, which are easy to handle and process further. Processing materials such as aluminum (Al), magnesium (Mg), and copper (Cu) using DCM is feasible due to lower force requirements. Despite many advantages of direct conversion methods, chips have certain limitations. The disadvantages of using some conventional and unconventional metal recycling methods are presented in Fig. 3 (Dhiman et al., 2021).

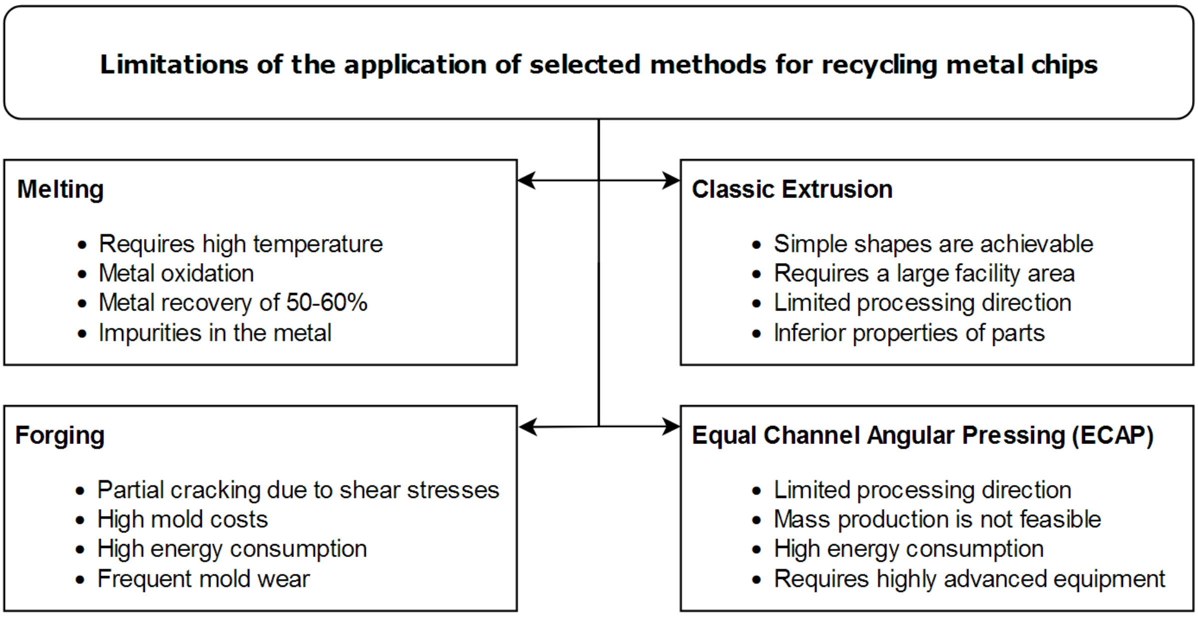
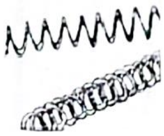


Fig. 3. Limitations of the application of selected direct conversion methods for recycling metal chips (Dhiman et al., 2021).

Equal Channel Angular Pressing (ECAP) is characterized by limited processing direction, high energy consumption, the need for advanced equipment, and is not suitable for mass production. Melting generates high temperatures, leading to metal oxidation, introduces impurities, and achieves metal recovery rates of only 50-60%. Classic extrusion allows for the formation of simple shapes but requires a large facility area, it has a limited processing direction, and produces parts with inferior properties. Forging is costly due to the use of dies that wear out quickly, it consumes a lot of energy, and can cause partial material cracking (Dhiman et al., 2021; Lee et al., 2017).

Considering that significant amounts of industrial waste, primarily chips, are generated during the machining of metals, especially aluminum and magnesium alloys (Table 3), the issue of proper management of this waste, including the use of recycling processes, is very important.

Table 3. Standard chips forms acc. to ISO 3685.

1 Ribbon chips	**2 Tubular chips**	**3 Spiral chips**	**4 Washer type helical chips**	**5 Conical helical chips**	**6 Arc chips**	**7 Elemental chips**	**8 Needle chips**
1.1 Long 	2.1 Long 	3.1 Flat 	4.1 Long 	5.1 Long  `1	6.1 Connected 		
1.2 Short 	2.2 Short 	3.2 Conical 	4.2 Short 	5.2 Short 	6.2 Loose 		
1.3 Snarled 	2.3 Snarled 		4.3 Snarled 	5.3 Snarled 			

Chips, which are waste generated in the machining of aluminum and magnesium alloys in the aerospace and automotive industries—such as turning, milling, drilling, reaming, tapping, and cutting—can serve as a source for recovering input material for use in other shaping technologies, primarily plastic deformation processes.

In the machining process of aluminum alloys, the same types of chips can be produced as when processing other materials. The most commonly encountered chips are ribbon chips and spiral chips, along with their variations. The type of chip is influenced by the shape of the cutting edge (chip breaker) and the cutting parameters.

The cutting temperature has an indirect effect on the chip formation. While machining with emulsions as cutting fluids results in long spiral chips, machining the same alloy dry under the same cutting parameters produces short spiral chips (Feld, 1984).

During the machining of magnesium alloys, short chips are most commonly produced (due to the formation of serrated chips), which are easy to remove from the machine tool (Kłonica et al., 2015; Oczoś, 2009).

The KOBO (Korbel and Bochniak method of plastic forming) extrusion process (Korbel & Bochniak, 1998) is one of the very promising recycling methods as it helps eliminate the previously described limitations of recycling metal chips. This method allows for the consolidation of chips into a solid material through pressing of scrap at low-temperature(Korbel et al., 2016). The melting stage is replaced by hot extrusion, resulting in the direct remelting of waste (Dybiec, 2008). An additional advantage of recycling using the KOBO method is the preservation of the mechanical and plastic properties of the alloy, and in some cases, even achieving better parameters than those of solid material (Bochniak et al., 2023; Dybiec, 2007; Xu et al., 2012; Watanabe et al., 2001). Low-temperature consolidation minimizes material losses and energy consumption by as much as five times (Chmura & Gronostajski, 2000).

Characterizing waste from metallic materials in terms of type, material properties, geometric forms, mechanical properties, and the type and properties of industrial impurities (such as lubricants, oils, and emulsions) is essential for developing the input material preparation for the KOBO extrusion process (Bochniak, 2009) and for selecting the parameters of that process.

Chips, as a specific type of waste, have the largest quantitative, volumetric, weight, and percentage share in the overall metallic waste. They are characterized by specific features resulting from:

- the types of metallic materials and their origin from a given machining technology,
- geometry (shape and size),
- the potential for consolidation (forming input materials for subsequent processing steps, including the KOBO extrusion process).

Chips represent a significant potential as a relatively inexpensive input material for further plastic processing. The geometry of the chips affects the consolidation process (Topolski et al., 2021), as their characteristics lead to interlocking, adhesion, and blockage. In briquettes, there is a smaller number of voids, but the connections between chips are weaker, making it difficult to form strong bonds. Thick chips create a structure that is more challenging to undergo elastic and plastic deformation. A properly prepared preliminary consolidation process for chips into briquettes is crucial (as illustrated in Fig. 4).

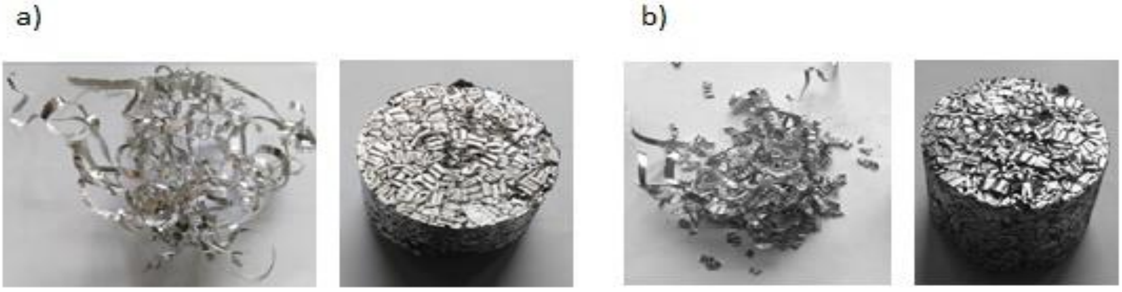


Fig. 4. Post-processing chips of a) 2024 alloy and b) 7075 alloy in fragmented and briquetted forms.

An example of a promising and energy-efficient recycling process for fragmented metallic fractions (wastes and chips) is the KOBO extrusion process (Bochniak, 2009; Pawłowska et al., 2019; Topolski & Ostachowski, 2021). Selected sample results from the KOBO process show that pre-consolidated billets in the form of briquettes can be effectively processed through KOBO extrusion when the following parameters are appropriately selected:

- Reverse die rotation angle (2-8 degrees).
- Die oscillation frequency (2-10 Hz).
- Extrusion rate (adjusted to the extrusion ratio and type of metal being extruded).
- Input material at room temperature (without preheating the input material).
- Extrusion ratio.

The KOBO method is characterized by its ability to achieve excellent mechanical properties in the products, which are optimal at room temperature deformation and offer superplasticity at higher temperatures (Bochniak et al., 2023). The preparation and execution of the KOBO process are schematically presented in Fig. 5. The KOBO extrusion press is shown in Fig. 6.

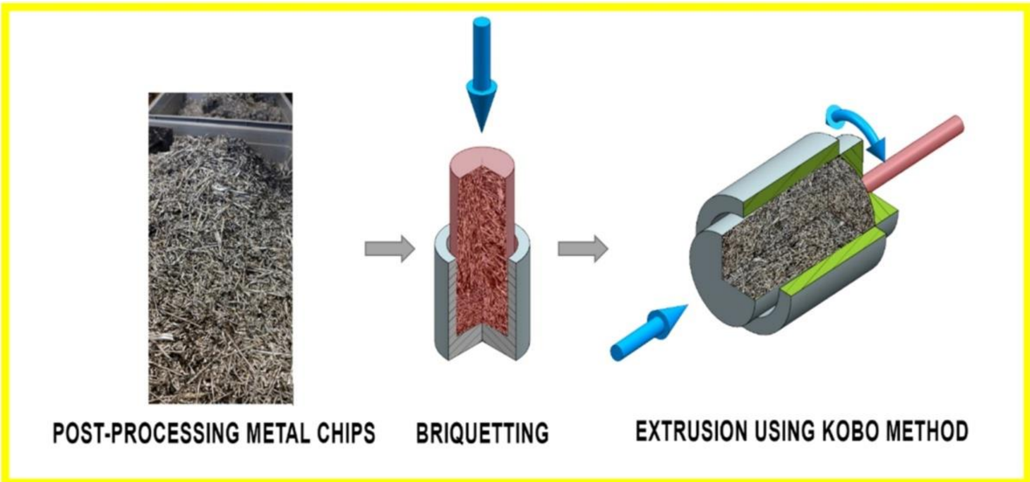


Fig. 5. Scheme of the preparation and execution of the KOBO extrusion process.

The extrudates obtained through this method demonstrated very positive characteristics, as confirmed by the results of mechanical property tests, including tensile testing results (Fig. 5) and the analysis of the micro and macrostructure examined on the cross-section of the extruded part, e.g. Fig. 6. Comparison of mechanical properties of extruded solid billets and consolidated industrial chips by the KOBO method is presented in Fig. 7.

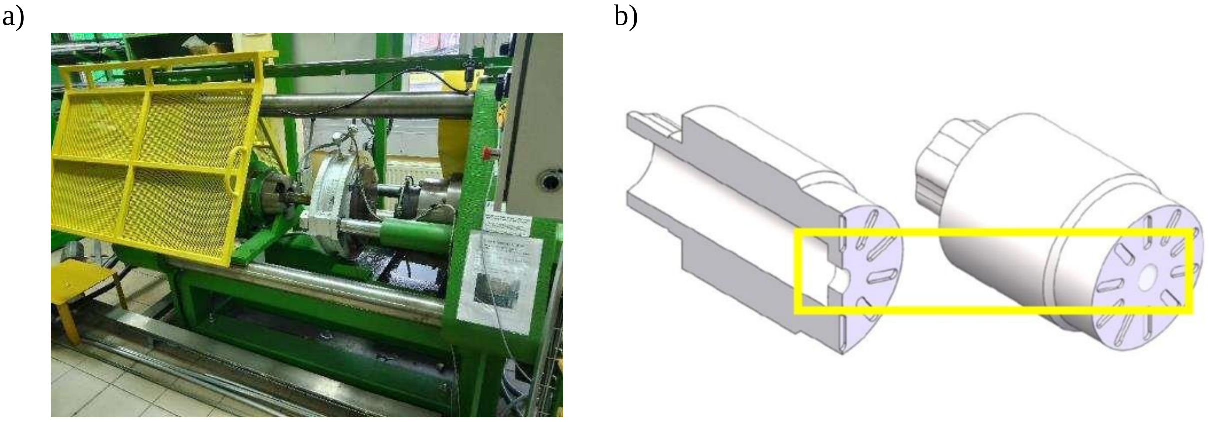


Fig. 6. Laboratory stand: a) KOBO extrusion press, b) dies used in the KOBO process.

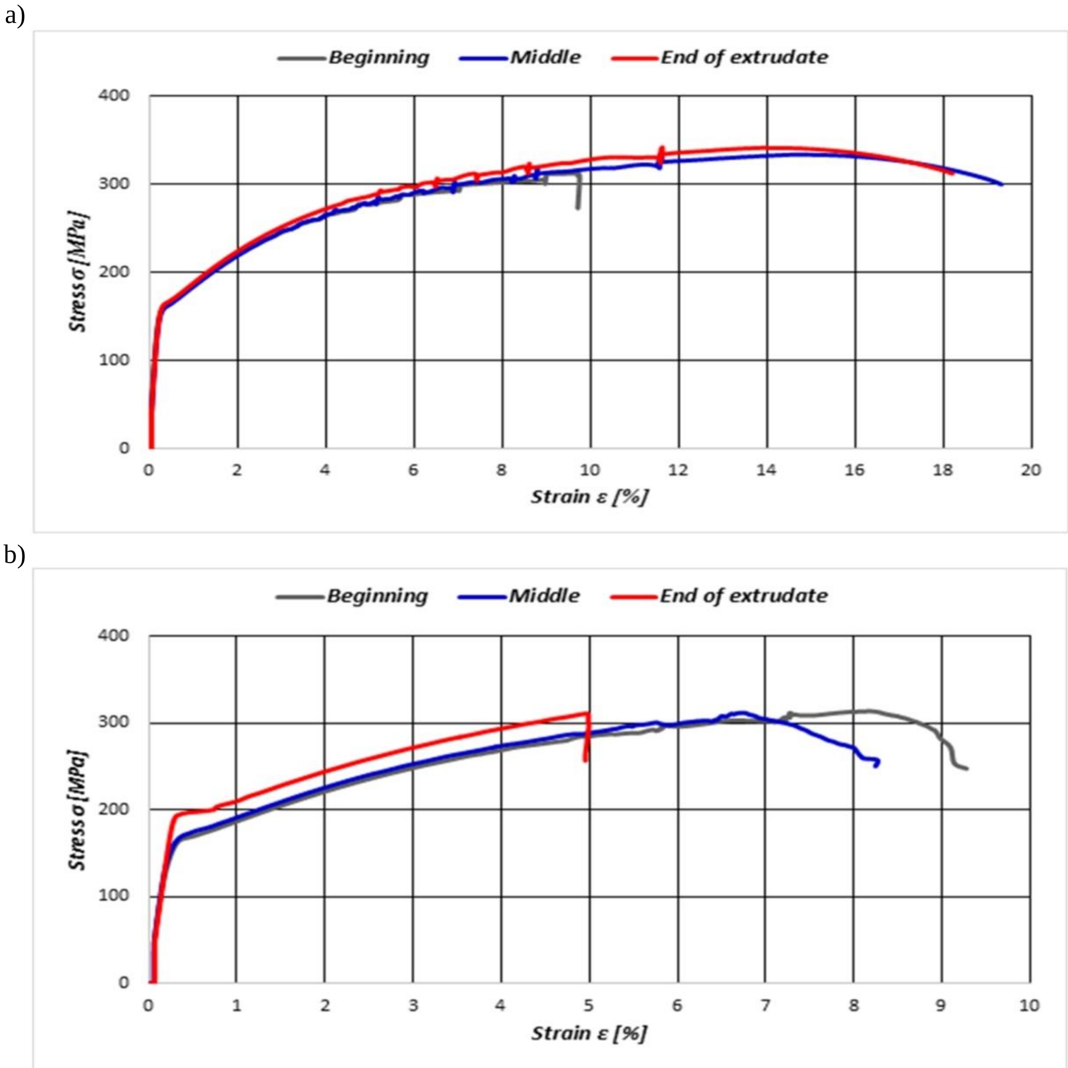


Fig. 7. Comparison of mechanical properties of extruded solid billets and consolidated industrial chips by the KOBO method
a) Tensile curves for φ = 10 mm rods obtained by KOBO method consolidation of industrial chips from aluminum alloy 2024
b) Tensile curves for φ = 10 mm rods from aluminum alloy 2024 – solid billet.

It is important to note the uniform values of the mechanical properties of the extruded product (homogeneity of properties along the length of the extrudate) in the case of product extruded from briquetted chips compared to profile extruded using solid billets (see Table 4). This allows for the production of 'long' products with any desired cross-sectional shape (profile), as stated in the publication (Korbel et al., 2016).

Table 4. Comparison of the properties of the compact during the KOBO extrusion (samples taken from the beginning, middle, and end of extrudate) using input in the form of briquetted chips, and input in the form of solid billets.

Chips				Solid billet			
Alloy / features	UTS [MPa]	YS [MPa]	A [%]	Alloy / features	UTS [MPa]	YS [MPa]	A [%]
2024 – in the beginning	290	161	9.2	2024 – in the beginning	286	163	9.7
2024 – in the middle	299	165	19.3	2024 – in the middle	292	171	8.2
2024 – at the end	306	171	18.2	2024 – at the end	296	196	4.9

The results of plastic deformation of the input material in the form of briquetted chips, assessed on the basis of the analysis of the internal structure of the extruded profile, indicate a satisfactory consolidation effect close to full consolidation (Fig. 8).

a) b)

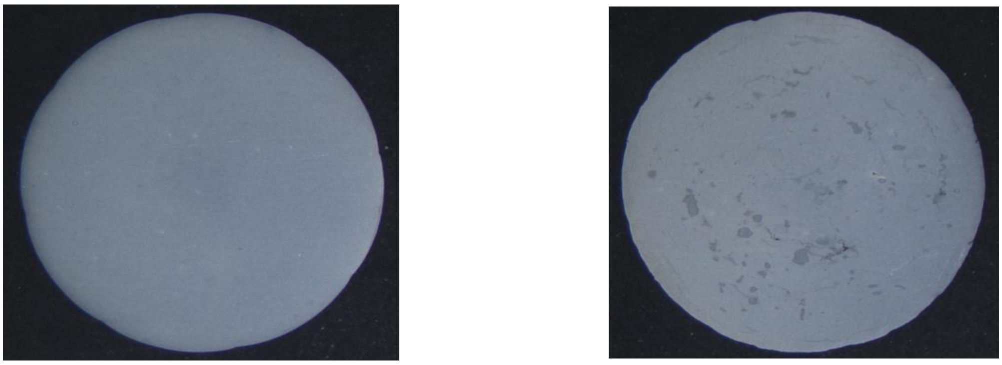


Fig. 8. Macrostructure of the sample from aluminum 2024 alloy a) from the extrusion obtained in the KOBO process using a solid billet, b) from the extrusion obtained in the KOBO process using briquetted chips.

The presented examples of research results regarding the effect of using the KOBO extrusion process for recycling industrial wastes, primarily chips from metallic materials, confirm the validity of employing this process for this purpose.

3. Summary

The demonstrated and documented necessity for seeking and implementing recycling processes in the global economy justifies conducting research aimed at material savings across various industries, minimizing energy consumption, and avoiding adverse environmental impacts. This is particularly relevant for metallic materials, which, in the form of various types of industrial waste, pose a significant recycling challenge. Chips from machining processes represent a large portion of this waste. Their recycling can be achieved through the innovative low-temperature KOBO extrusion, which is a low-energy process that ensures favorable properties of the obtained products.

All types of investigated metal chips that were consolidated and plastically deformed in the KOBO extrusion process led to the production of rods, regardless of the cleanliness and properties, type of chips, as well as their shape and thickness. It has been shown that despite significant differences in the properties of the chips, the KOBO extrusion process allowed for the conversion of chips into solid material.

It has been demonstrated that all rods produced after recycling possess a solid, monolithic structure in the raw state, which is homogeneous, consolidated, and nearly fully dense. No significant macro or micro defects such as cracks, porosity, or discontinuities were observed.

Using the method of large plastic deformation through the KOBO extrusion process, it is possible to modify the material via strengthening to such an extent that the values of its mechanical properties exceed those obtained after heat treatment.

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Obecne Możliwości Recyklingu Przemysłowych Odpadów Metalowych: Możliwości Procesu Wyciskania KOBO

Streszczenie

Praca dotyczy problematyki wykorzystania odpadów w świetle obowiązujących regulacji prawnych w Polsce i Unii Europejskiej. Wskazano istotę recyklingu, ze zwróceniem szczególnej uwagi na pierwiastki metali, których złoża naturalne są ograniczone. Wskazano porównanie pierwotnych metod wydobycia metali oraz odzysk metali (pochodzących ze źródeł wtórnych) z wykorzystaniem metod recyklingu w stanie stałym oraz bez przetopu. Dokonano analizy niektórych sposobów recyklingu poprodukcyjnych odpadów metalowych. Szczególną uwagę zwrócono na metalowe wióra oraz towarzyszące im substancje smarno-chłodzące. Zaprezentowano innowacyjny proces recyklingowy – wyciskanie KOBO odpadów metalowych w postaci wiórów, przykładowe wyniki badań oraz wykaz korzyści płynących z wykorzystania tego procesu do produkcji kształtowników metalowych.

Słowa kluczowe: recykling, odpady poprodukcyjne, wykorzystanie odpadów przemysłowych, regulacje prawne, wyciskanie KOBO